LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although portions of this report are not reproducible, it is being made available in microfiche to facilitate the availability of those parts of the document which are legible.

3

CONF 871012-2

LA-UR -87-877

LA-UR--87-877

DE87 007490

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE Conversion of Borehole Stoneley Waves to Channel Waves in Coal

AUTHOR(S) Paul A. Johnson and James N. Albright

SUBMITTED TO SEG 57th Annual Meeting

MASTER

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4

Please do not fold!

Conversion of Borehole Stoneley Waves to Channel Waves in Coal

Paul A. Johnson, and James N. Albright, Los Alamos National Laboratory

SUMMARY

Evidence for the mode conversion of borehole Stoneley waves to stratigraphically guided channel waves was discovered in data from a crosswell acoustic experiment conducted between wells penetrating thin coal strata located near Rifle, Colorado. Traveltime moveout observations show that borehole Stoneley waves, excited by a transmitter positioned at substantial distances in one well above and below a coal stratum at 202? m depth, underwent partial conversion to a channel wave propagating away from the well through the coal. In an adjacent well the channel wave was detected at receiver locations within the coal, and borehole Stoneley waves, arising from a second partial conversion of channel waves, were detected at locations above and below the coal. The observed channel wave is inferred to be the third-higher Rayleigh mode based on comparison of the measured group velocity with theoretically derived dispersion curves. The identification of the mode conversion between borehole and stratigraphically guided waves is significant because coal penetrated by multiple wells may be detected without placing an acoustic transmitter or receiver within the waveguide.

INTRODUCTION

The need to know if a coal seam is faulted, or whether in-seam discontinuties exist, has been the impetus behind many studies about guided waves in coal, commonly referred to as channel waves. Evison (19[illegible]) and Krey (19[illegible]) were the first to publish observations of guided waves in coal and to recognize that they may be used to determine whether faults exist. [illegible] workers have elaborated on [illegible] waves to detect discontinuities in coal seams, including more recently Dresen et al. (19[illegible]) and [illegible] et al. (19[illegible]). These studies deal exclusively with channel waves that are both generated and detected within the coal.

Examination of our crosswell acoustic data obtained in wells penetrating a coal-bearing stratigraphy shows that energy may be propagated between wells through coal as a channel wave when either the transmitting or receiving transducer is placed within or outside of coal. When neither transducer is located in the coal, which is the situation generally encountered in a crosswell acoustic survey, some fraction of the energy launched at the transmitter as a borehole guided wave is expended in the excitation of a channel wave in the coal, which subsequently excites a second borehole guided wave in the well in which the receiver is placed. Because the borehole guided wave in question is a Stoneley wave, the path followed in this manner between the transmitter and receiver will be referred to as the Stoneley channel Stoneley (SCS) propagation path.

In the following sections, we describe the geology in which the data were obtained, the method of acquiring the data, and relevant logging tool parameters. The basis for the identification of the borehole propagation mode is then given. Next, the basis of the SCS propagation path hypothesis as well as the sufficiency of the hypothesis is reviewed. Finally, the probable nature of the channel wave is discussed in terms of calculated dispersion curves for Rayleigh wave propagation in layered media.

RIFLE, COLORADO, CROSSWELL MEASUREMENTS

Data were taken at the Department of Energy Multi-Well Experiment (MWX) Site in the Piceance Basin near Rifle, Colorado (Northrop et al., 1983). Extensive crosswell acoustic data were acquired in a depth interval (1830-2075 m) that includes a stratigraphy of lenticular deposits of sandstone and shale interspersed with thin seams of low-volatile bituminous coal. P- and S-wave signals were transmitted between two wells which were separated by 34 m as determined from borehole deviation surveys.

The borehole tools used at the MWX Site were specially designed and fabricated at the Los Alamos National Laboratory for crosswell research applications (Dennis et al., 1985). The magnetostrictive source and piezoelectric receiver are cylindrical in shape; the receiver has a flat response over the frequency band of the acquired signals (2.2 ± 1.0 kHz). The geometry in which data were acquired is shown in Figure 1. In an operation termed a scan, the receiver is held stationary in one well while the transmitter in an adjacent well is moved from a position above to a position below the receiver depth in what is called a transmitter run.

BOREHOLE GUIDED WAVE PROPAGATION

Observations of recorded velocity moveout suggest that the borehole propagation segment of the SCS path is a Stoneley wave. Figure 2 is a representative example of a scan showing signals that include SCS waveforms. The arrival of the guided wave is denoted by G. The solid line marked P gives the estimated arrival time of the P-wave based on the average velocity of the depth interval in which the data were acquired. Note especially that the time delay of waveform G changes linearly with transmitter depth, "moving out" at approximately 0.6? ms/m. The observed moveout of the guided wave can only be accounted for if the propagation path between transmitter and receiver includes a segment of travel along the transmitter well; direct, reflected, or refracted arrivals would display nonlinear moveout. The moveout corresponds to a borehole guided wave having the velocity V of 1.4? m/ms, the frequency is approximately 2.2 kHz and little or no dispersion is evident.

Depending on the excitation frequency, either Stoneley waves or both Stoneley and pseudo-Rayleigh waves may propagate as guided waves in fluid-filled boreholes. Cheng and Toksöz (1981) presented a calculation for a geometry and velocity similar to the MWX borehole situation which showed that pseudo-Rayleigh waves do not exist below a cutoff frequency of approximately 9 kHz, while Stoneley waves exist at all frequencies and exhibit little dispersion. Thus the guided wave G can reasonably be inferred to be launched and to travel as a Stoneley wave whenever its propagation path includes a segment of travel along the well of the transmitting transducer. Furthermore, if the waveform can be shown to have traveled along the well of the receiving transducer, its propagation along that path must also be as a Stoneley wave.

BOREHOLE STONELEY WAVE MODE CONVERSIONS

It is well known that Stoneley waves are produced by body wave conversion at geologic discontinuities, collars and other irregularities within boreholes; the reverse process of borehole Stoneley wave to body wave conversion at such irregularities has also been observed (e.g. White, 1965; Hardage, 1981; Wong, 1981). With the exception of casing collars at known locations, no borehole irregularities occur in the depth interval studied in the MWX wells. Geologic discontinuities, principally boundaries between sandstones and thin coal seams, however, are common in the Mesa Verde formation. Where these discontinuities occur, mode conversions involving Stoneley waves are possible. The theoretical basis for the various mode conversions between body waves and Stoneley waves has been explored by White (1965), Beydoun et al. (1984), and others. None of these studies are adequate to explain the observations we report.

Consider the general case shown in Figure 3a for geologic discontinuities A and B in boreholes containing a transmitter T and a receiver R, respectively. Paths with a designation that include A or B indicate that borehole Stoneley wave propagation occurs along some length of the well in which a transducer is placed. The relationship among the arrival times of signals propagating along each path is illustrated in Figure 3b. According to Figure 3, if Stoneley wave propagation occurs in both wells or only in the well of the source transducer, then linear moveout will be observed. In these instances, a chevron pattern results, and the minimum travel time at the apex of the chevron occurs at the depth where Stoneley wave conversion is taking place.

In processing scan data, discrimination between upward and downward launched waves is achieved through the proper choice of the sign for a borehole Stoneley wave moveout correction in stacking signals. In practice, a composite of borehole Stoneley wave traces is useful for determining the apex of a chevron. To form a composite trace, a stack of signals made to enhance upward launched borehole Stoneley waves is simply added to a stack of the same signals which enhances downward launched borehole Stoneley waves. Scan data processed to make composite traces will be discussed in the following section.

CHANNEL WAVE OBSERVATIONS

Physical evidence supporting the SCS propagation path hypothesis is given in Figures 4 and 5. Figure 4 shows composite stacked traces for two scans having receiver positions above and below the coal stratum. The chevrons' apexes in this figure indicate that the waveform G must have propagated along a TABR path according to Figure 3b where A and B are at the same depth. Since the chevron apex occurs at a depth where geophysical log data indicate a coal layer, and because the travel path must be a TABR path as shown in Figure 3, the observations indicate passage of the wave through the coal layer. The dashed line in Figure 4 connects the coal layer depth for each scan or, equivalently, the apexes of the phase.

Portions of scans for receiver locations above, below, and within the coal are shown in Figure 5. Each signal is presented as the square of the complex trace of the received signal to simplify the wavetrains and accentuate the higher amplitude arrivals (Farnback, 1975). In these cases, there was no stacking. Traces with flat-topped peaks have been clipped in plotting.

Figure 5a shows the onset of the P-wave arrival P_{SS} in the sandstone. Traces for which the transmitter and receiver are both located in the coal (Figure 5b; 2021.8 < Z_T < 2022.7 m) are those where the transmission path between boreholes does not include any segment of borehole Stoneley wave propagation. In Figure 5b, the onset of the P-wave arrival in the coal P_c can clearly be seen. Following the P_c arrival is a high amplitude phase that is slower than the shear wave velocity in the surrounding rock, but is too fast to be a shear wave in the coal layer. Because the coal acts as a waveguide since the surrounding rock is of higher velocity and because of the arrival time of the above wave, we infer that this phase is a guided or channel wave.

The signals with blackened crests occur when the transmitter is located in the coal and propagation between boreholes is by a channel wave within the coal to receiver location either directly above or below the coal (Figures 5a and 5c; 2021.8 < Z_T < 2022.7 m). These signals represent waves that have traveled a short distance as Stoneley waves in the receiver borehole after having traversed between boreholes entirely through coal. Traces of SCS signals transmitted between boreholes when neither transmitter nor receiver is located in the coal (Figures 5a and 5c; Z_T < 2021.8 and Z_T > 2022.7 m) are labelled G in the figure.

CHANNEL WAVE PROPAGATION MODE

The dispersion curves in Figure 6 for the group velocity of generalized Rayleigh waves through the coal were calculated using the approach of Krey

(19[illegible]) and Peterson (1979). The appropriate velocities and densities are listed in Table 1. The group velocity measurement of the channel wave was made when both source and receiver were in the coal layer as shown in Figure 5b.

In Figure 6, the measured group velocity for the channel wave through the coal lies near the third-higher Rayleigh mode, a symmetric mode. This is not surprising since excitation of the fundamental mode, or any other antisymmetric mode, with a symmetric source is very inefficient (Peterson, 1979). Excitation of any given mode is also dependent on the location of the source and receiver in relation to a mode's various nodes and antinodes. It is not clear, however, why the observed group velocities do not occur closer to that of the Airy phase as one might expect. This observation cannot be attributed to reasonable measurement errors in the values listed in Table 2. Even if layer P-wave or S-wave velocities are in error by as much as ±10%, the dispersion curves for the various modes are not substantially different from those presented.

CONCLUSIONS

From data collected in a crosswell acoustic survey, we observe a phase that propagates along the transmitter borehole as a Stoneley wave, then through mode conversion travels between holes as a channel wave in coal, and subsequently is converted back to a Stoneley wave in the receiver borehole. The observation is significant because coal penetrated by multiple wells may be detected without placing an acoustic transmitter or receiver in the waveguide. Such observations could be useful for the identification of layer continuity between boreholes and the study of deep coals.

ACKNOWLEDGMENTS

We are grateful for the Rayleigh and Love wave dispersion code provided by Frank Hadsell and for helpful discussions with Steve Peterson and Robert Herrmann. Thanks also to Mike Fehler and W. Scott Phillips for [illegible] technical discussions and for critical review of this paper. Funding for this work was provided under the auspices of the US Department of Energy Unconventional Gas Recovery Program, Karl-Heinz Frohne, Program Manager. The Los Alamos Geosciences Instrumentation Group, led by Bert Dennis, provided the borehole instrumentation and field support necessary to conduct this study.

REFERENCES

Hardin, E. L., Cheng, C. H. and Toksöz, M. N., 1986, Detection of subsurface fractures and permeable zones by the analysis of tube waves, in Toksöz, M. N. and Stewart, R. R., Eds., Handbook of geophysical exploration, V. 14B, Vertical seismic profiling, Part B: Advanced concepts, Geophysical Press, London.

Cheng, C. H. and Toksöz, M. N., 1981, Elastic wave propagation in a fluid-filled borehole and synthetic acoustic logs: Geophysics, 46, 104[illegible].

Dennis, B. R., Koczan, S. P. and Stephani, E. L., 198[illegible], High temperature borehole instrumentation. Los Alamos National Laboratory report LA-10558-HDR.

Dreser, L., Kerner, C., and Kuhback, B., 1985, The influence of an asymmetry in the sequence rock/coal/rock on the propagation of Rayleigh seam waves: Geophys. Prospect., 33, 519-539.

Edwards, S. A., Asten, M. W. and Drake, L. A., P-SV wave scattering by coal-seam inhomogeneities: Geophysics, 50, 217-223.

Evison, F. F., 1955, A coal seam as a guide for seismic energy: Nature, 176, 1224-1225.

Farnback, J. S., 1975, The complex envelope in seismic signal analysis: Bull. Seismol. Soc. Am., 65, 951-962.

Hardage, B. A., 1981, An examination of tube wave noise in vertical seismic profiling data: Geophysics, 46, 892-903.

Krey, T. C., 1963, Channel waves as a tool of applied geophysics in coal mining: Geophysics, 28, 701-714.

Northrop, D. A., Sattler, A. R., Westhusing, J. K., 1983, Multi-Well Experiment: A field laboratory for tight gas sands: Proceedings SPE/DOE Symposium Low Permeability Gas Reservoirs, SPE/DOE 11646.

Peterson, S. D., 1979, Modal analysis of seismic guided waves: Ph.D dissertation, Colorado School of Mines.

White, J. E., 1965, Seismic waves - radiation transmission and attenuation: McGraw-Hill Book Co., Inc, New York.

Wong, J., Hurley, P., and West, G. F., 1983, Crosswell seismology and seismic imaging in crystalline rocks: Geophys. Res. Lett., 10, 686-689.

SEG

Society of Exploration Geophysicists

Return 3 copies of this form with completed manuscript before **March 15, 1987** to:
Technical Program Chairman Richard A. Cole, SEG 1987 Annual Meeting,
P.O. Box 702740, Tulsa, OK 74170-2740; or street address: 8801 So. Yale, Tulsa, OK 74137.

Captions

Figure captions and table captions should be listed below in the space provided. Captions must be short and concise; lengthy discussions should be limited to the body of the abstract.

Figure captions:

FIG 1. Schematic of crosswell scan geometry.

FIG 2. Crosswell scan centered at a receiver depth of 2024 m in which every 10th trace is plotted.

FIG 3. Waveform moveout of signals transmitted between wells. T-transmitter, R-receiver. A and B-locations where Stoneley wave conversions occur.

FIG 4. Composite traces from above and below the coal. G denotes the guided wave arrival.

FIG 5. Complex trace representation of scans near or within the coal in which every trace is plotted.

FIG 6. Dispersion curves of Rayleigh wave group velocity. Observed value shown by cross. Cutoff velocities shown by dashed lines.

Table captions:

Table 1. Velocities and Densities Relevant to Channel Wave Propagation.

Table 2.

Table 3.

Table 4.

Three copies of each table and figure are required.

TABLE 1

VELOCITIES AND DENSITIES RELEVANT TO CHANNEL WAVE PROPAGATION

	Velocity, m/ms				Density
Stratum	v_p(obs)	v_p(log)	v_s(calc)	v_C(obs)	
g/cc					
Upper ss	4.16	4.76	2.44		2.63
Coal	2.22	2.50	1.26	1.52	1.84
Lower ss	3.91	4.33	2.28		2.63

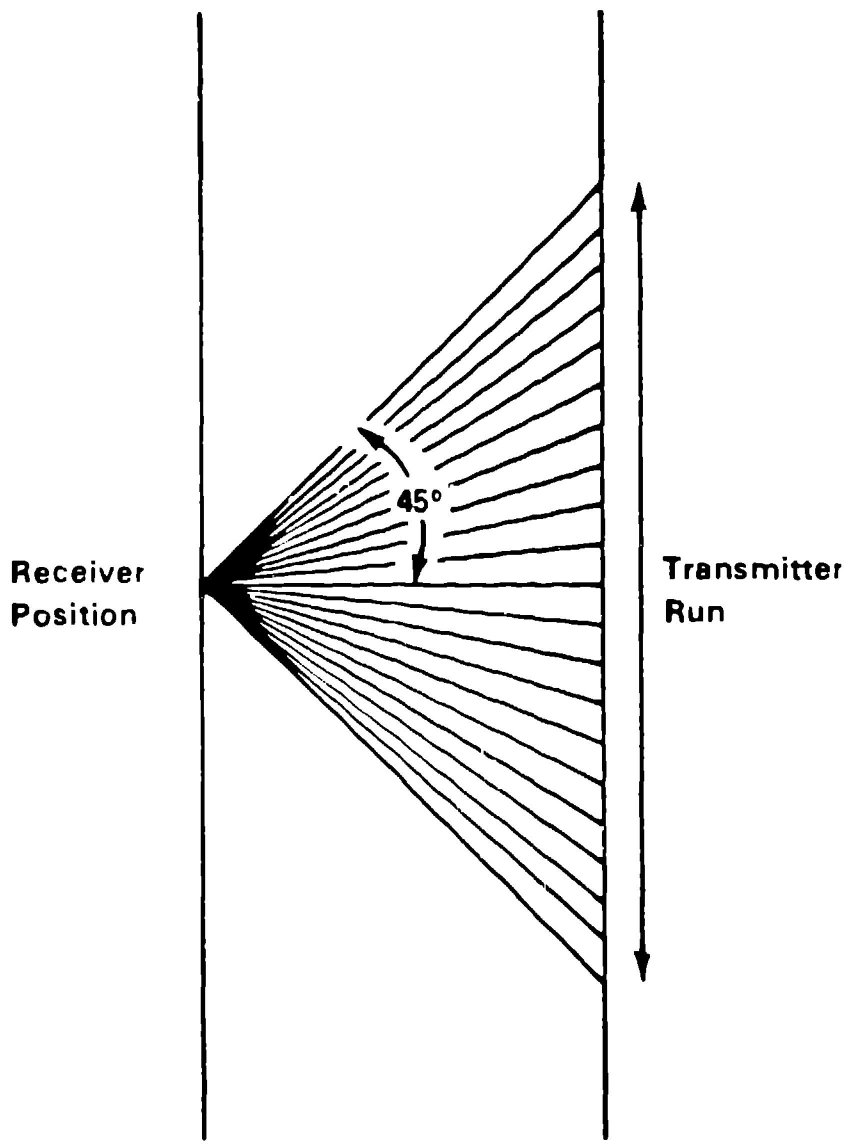
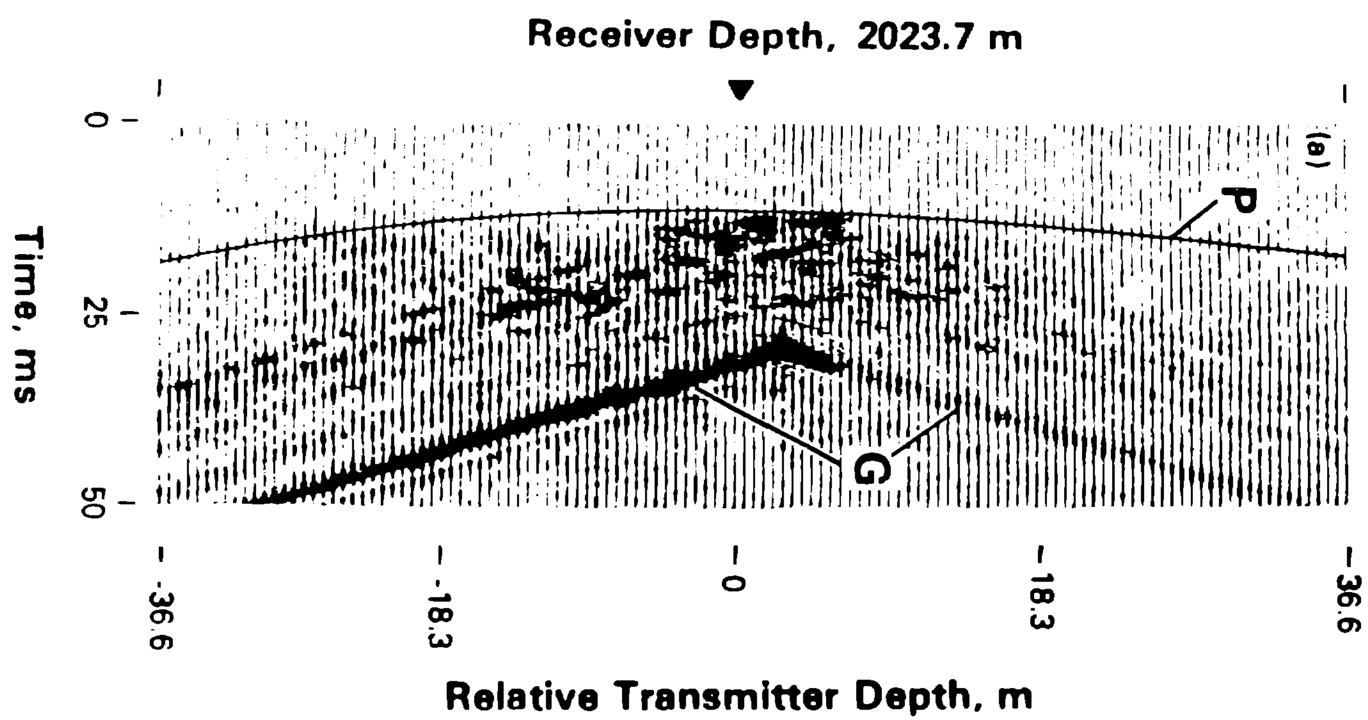
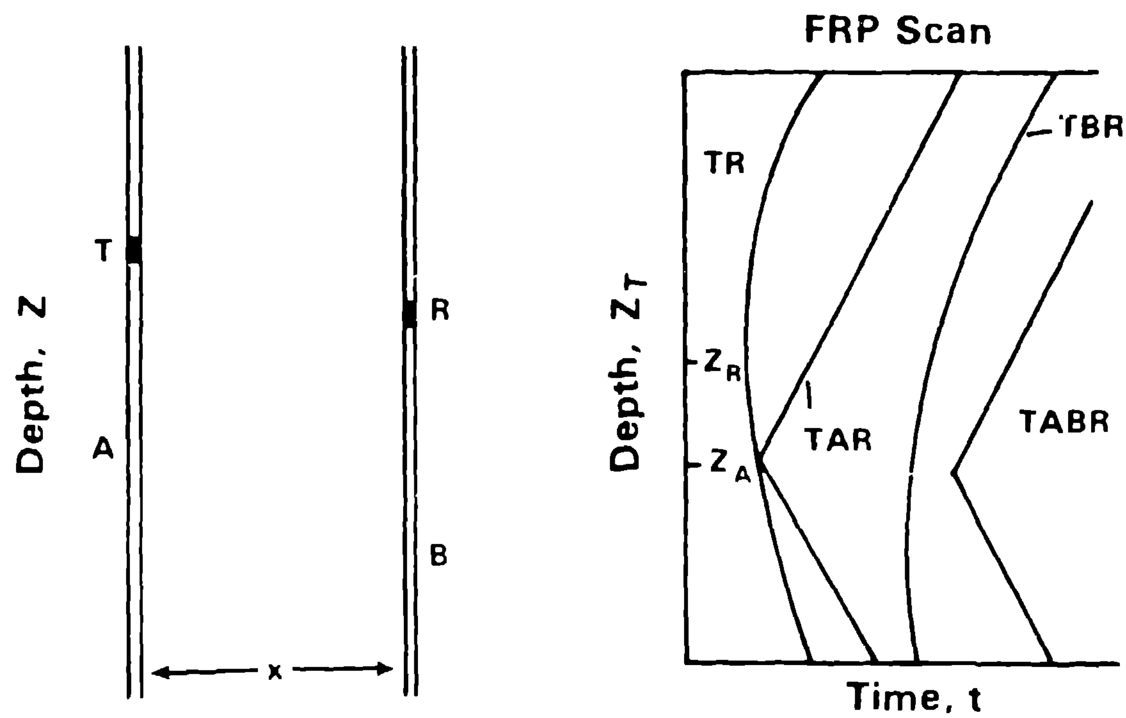

45°
Receiver
Position
Transmitter
Run

Fig. 2


Receiver Depth, 2023.7 m
(a)
P
G
Time, ms
0
25
50
-36.6
-18.3
0
18.3
36.6
Relative Transmitter Depth, m



(a) (b)

3 ↑

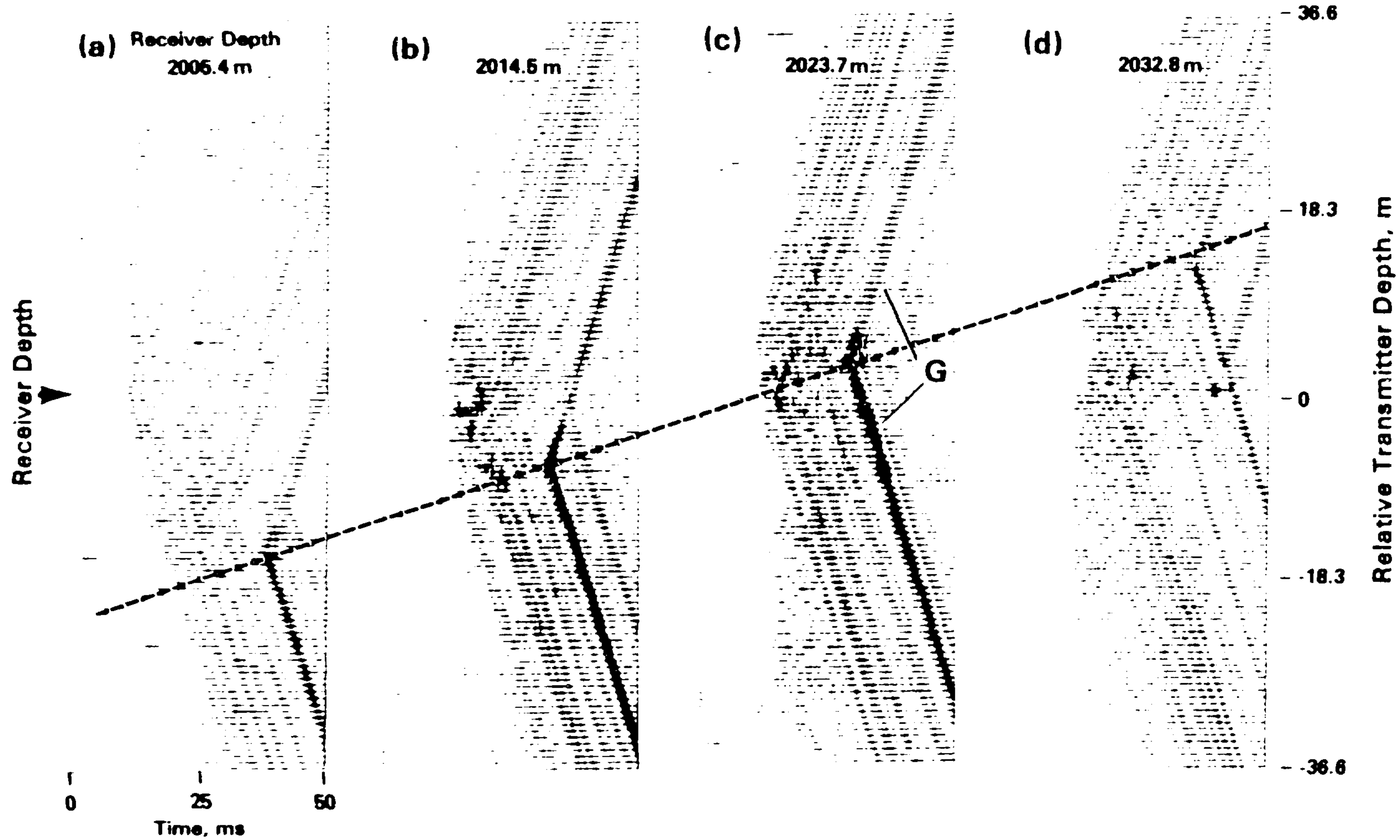
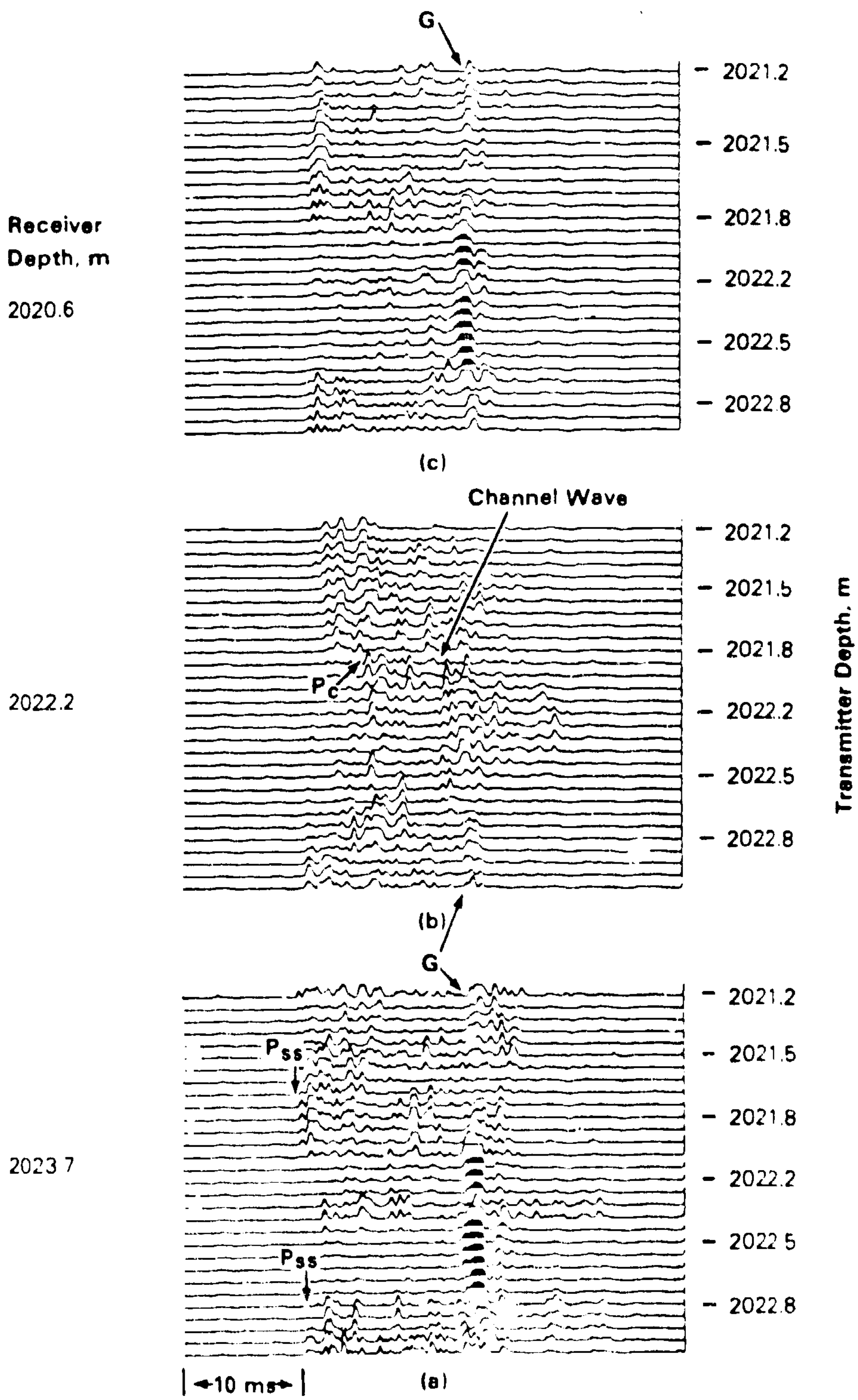

(a) Receiver Depth
2006.4 m
(b)
2014.5 m
(c)
2023.7 m
(d)
2032.8 m
Receiver Depth
G
36.6
18.3
0
-18.3
-36.6
Relative Transmitter Depth, m
0
25
50
Time, ms

Fig. 4 ↑



G
2021.2
2021.5
2021.8
2022.2
2022.5
2022.8
Receiver
Depth, m
2020.6
(c)
Channel Wave
P_c
2022.2
Transmitter Depth, m
(b)
G
P_{ss}
2023.7
(a)
10 ms

Group Velocity vs. Period